Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

BNL Magnet Capabilities and Projects

Kathleen Amm
Director, Magnet Division
ammk@bnl.gov

@BrookhavenLab

Outline

- Magnet division vision and mission
- History of magnet division
- Current capabilities and projects
  - Accelerator Upgrade Project
  - Electron Ion Collider
  - Testing capabilities – Magnet Development Program and Fusion
- Technologies for Future Circular Colliders
- Conclusions

Magnet Division

Vision-

To be a world class superconducting and electromagnetics team creating the future of superconducting magnet technology. This includes leadership in superconducting magnet technology, magnet development, manufacturing and testing with application to accelerator, science, fusion and industrial applications

Mission –

Utilize world class capabilities to:

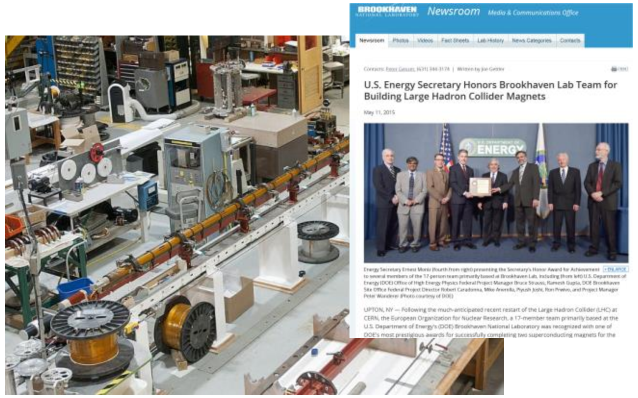
Advance the science and technology of superconducting magnets

Apply these technologies to support accelerators, fundamental science discoveries, energy and other industrial applications requiring high magnetic fields

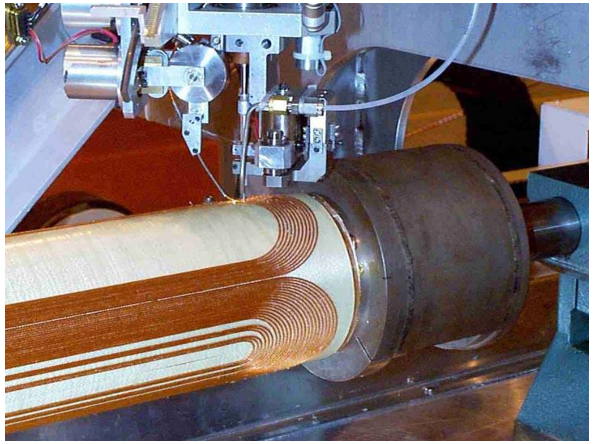
Ensure a strong national talent pool for superconducting magnet development in the US

Superconducting Magnet Division – a Rich History

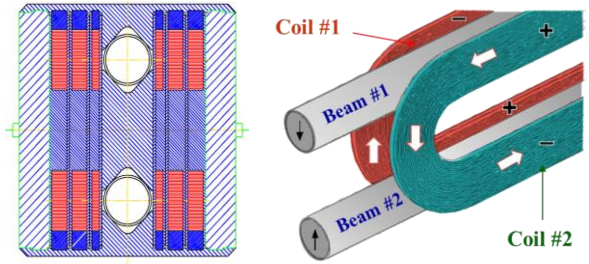
Relativistic Heavy Ion Collider – strong history of industrialization at Brookhaven



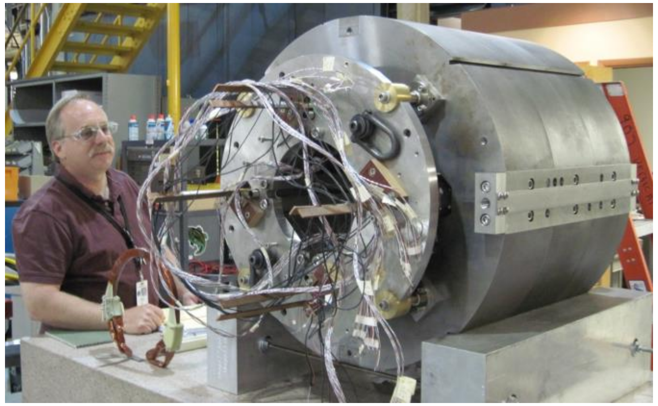
Magnets for Large Hadron Collider – Geneva, Switzerland



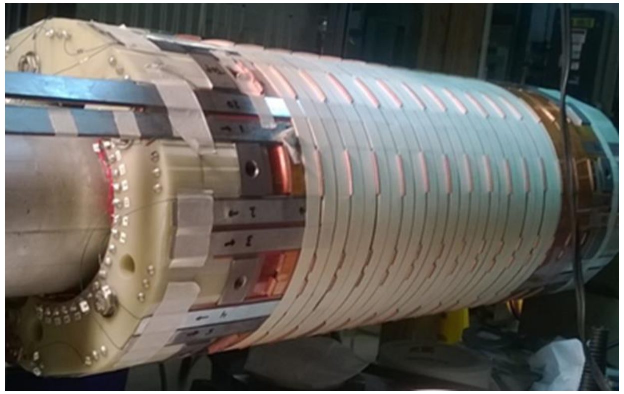
Hadron Electron Ring Accelerator magnet – Hamburg, Germany



R&D on Common Coil dipole designs



High temperature superconducting magnet for Facility for Rare Isotope Beams, Michigan State



High temperature superconducting magnetic energy storage device

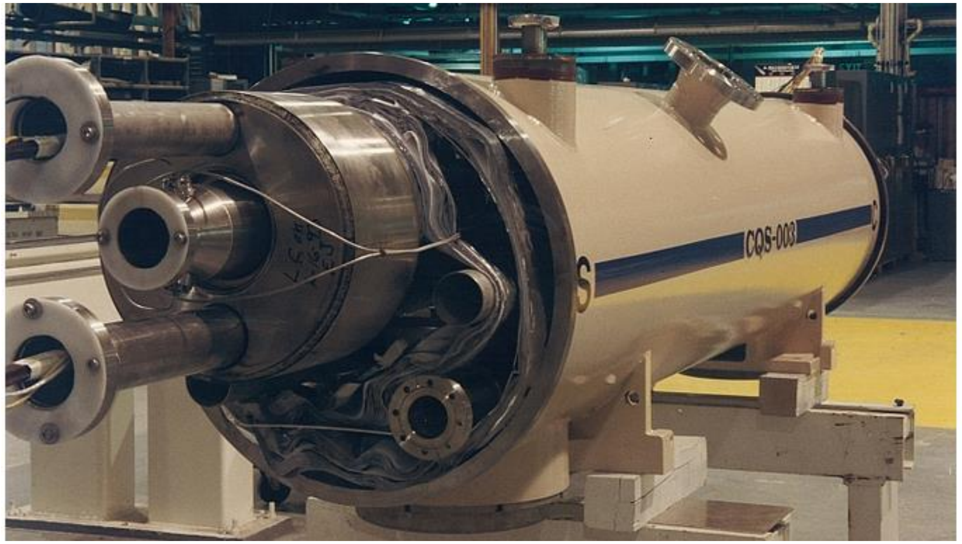
https://www.bnl.gov/magnets/projects.php

Brookhaven National Laboratory

Superconducting Magnets for RHIC

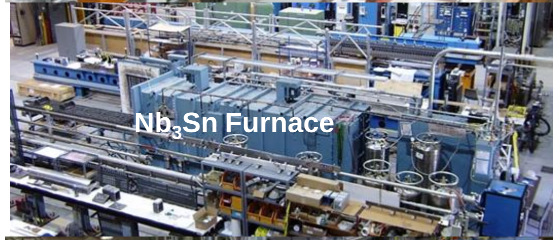
(a large number, all developed @BNL, some built @industry)

- BNL magnet division designed (all), built (all prototype) and tested (a fraction cold) sc magnets for RHIC
- RHIC commissioning went very well, partly because of the superb quench and field quality performance of the magnets
- Magnets operating well and will be used in EIC



REGULAR ARC COMPONENTS	
Dipoles	264
Quadrupoles	276
Sextupoles	276
Correctors	276
INSERTION COMPONENTS	
Standard Aperture (8 cm) Magnets	
Dipoles (D5I, D5O, D6, D8, D9)	96
Quadrupoles (Q4-Q9)	144
Trim quadrupoles (@ Q4, Q5, Q6)	72
Sextupoles at Q9	12
Correctors	144
Intermediate Aperture (10 cm) Magnets	
Dipoles (D0)	24
Helical Dipoles	12
Intermediate Aperture (13 cm) Magnets	
Quadrupoles (Q1-Q3)	72
Correctors	72
Large Aperture (18 cm) Magnets	
Dipoles (DX)12	
TOTALS	
Dipoles	408
Quadrupoles	492
Trim quadrupoles	72
Sextupoles	288
Correctors	492
Total magnets	1752

Magnet Division – Capabilities and Priorities



Vision: To be a world class superconducting and electromagnetics team creating the future of superconducting magnet technology.

Magnet Division staff deliver leadership in:

- Superconducting magnet technology
- Magnet development, manufacturing and testing with application to accelerator, science, fusion and industry

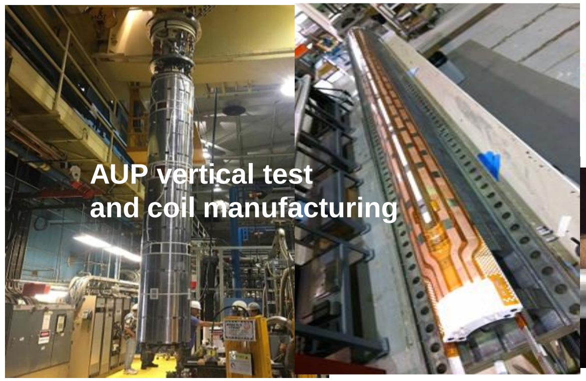
Capabilities:

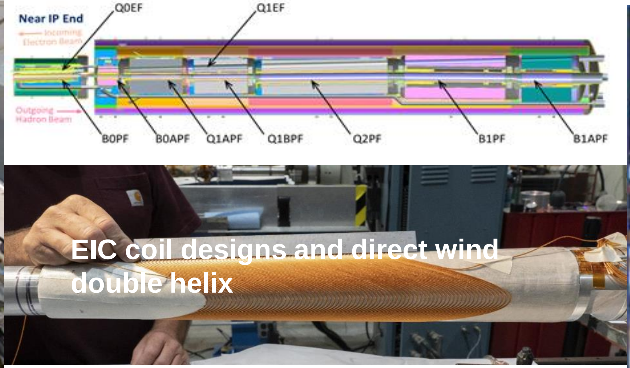
- LTS and HTS superconducting magnets - 10m Coil Winding Capability, Nb_3Sn furnace 4.2 m
- Direct wind magnets and facility -IR and Specialty Magnets, Precision Field Quality, 2.5m Coil Winding Capability
- Magnet Test facility - 1.9K, 22KA, 6.1m deep, 71cm dia.

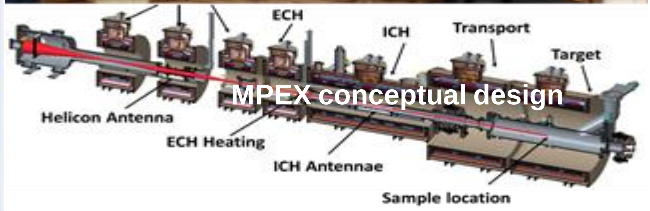
Current priorities:

- Accelerator Upgrade project – coil construction, vertical magnet test
- EIC magnets – IR, magnet measurement, RHIC magnet re-use
- Magnet Development Project – HTS/LTS hybrid, Diagnostics
- Fusion – INFUSE, ARPA-E (CFS), MPEX

Deliver superconducting applications for DOE (SC, ARPA-E, ...) and SPP (Power, Fusion,...)







Superconducting Magnet Division

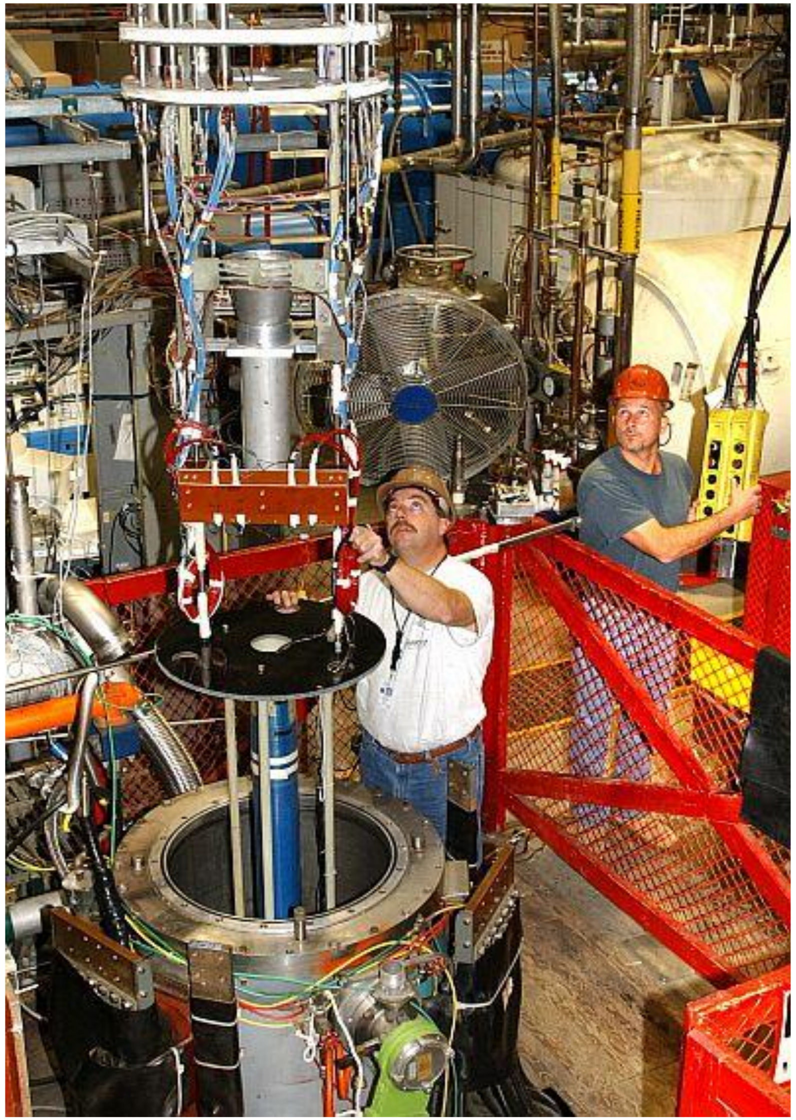
58,000 sq. ft. facility

Supports:

- Coil Winding – NbTi, Nb_3Sn, HTS
  - Unique direct wind capability for high precision specialty and IR magnets
- Vacuum Impregnation
- Coil Reaction
- Flexible vertical test stand
  - Operation down to 1.9K

Magnetic measurements

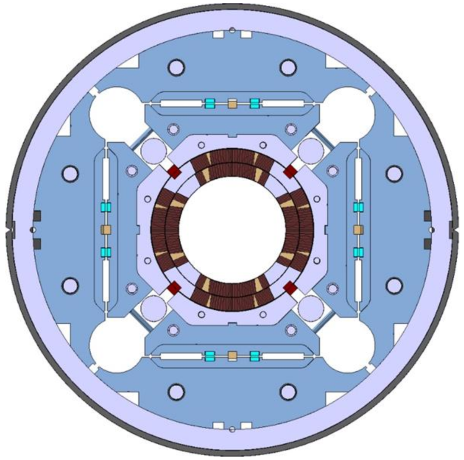
Estimate >$30M investment to replicate these capabilities

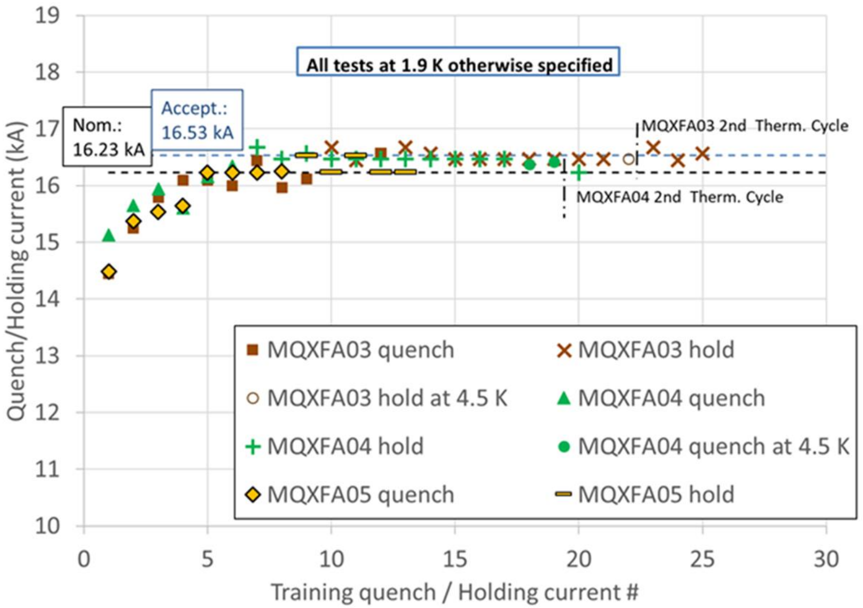


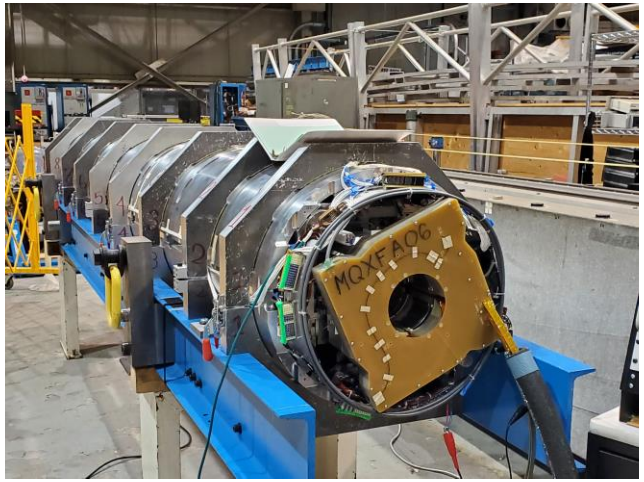
Accelerator Upgrade Project

BNL Scope

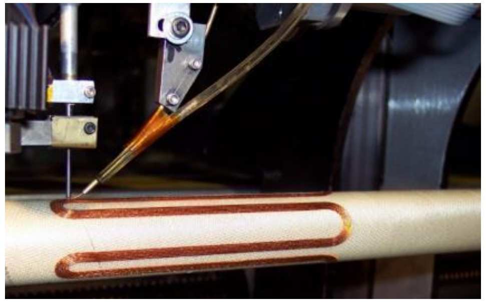
- Manufacture 47 4.2m quad coils
- Test 27 4.2 magnet cold masses





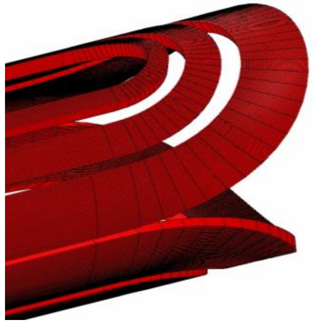


EIC Magnets Near IP Use Two Fabrication Techniques



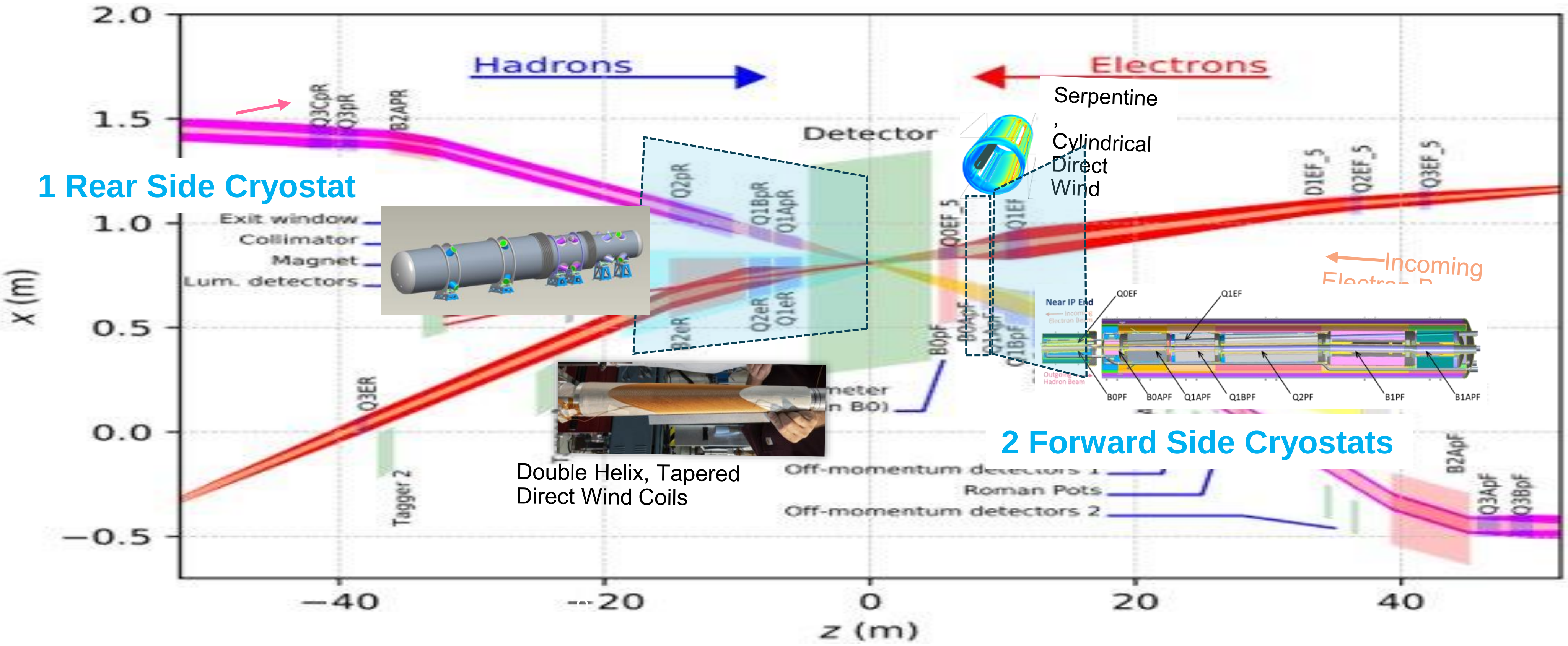
Both Serpentine and Double Helix coil patterns are wound on either tapered or cylindrical support tubes using 6-around-1, round cable (corrector coils use single-strand superconducting wire).

11 Direct Wind Magnets

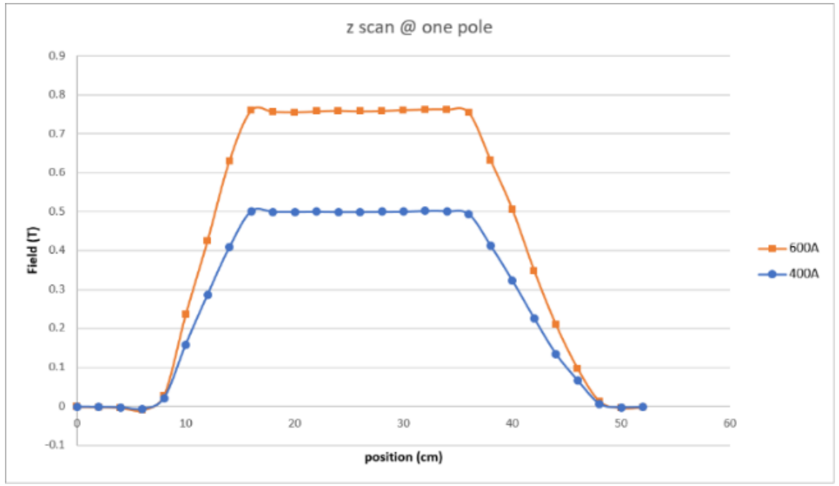


The large aperture forward hadron quadrupoles and dipoles use Rutherford style cable; note electron beam passes through holes cut in their yokes.

5 Collared Coil Magnets

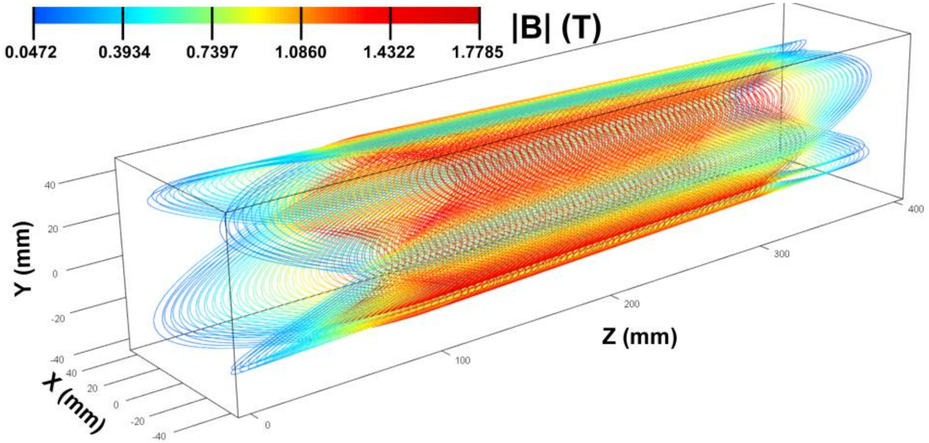


Tapered Double-Helix Magnet

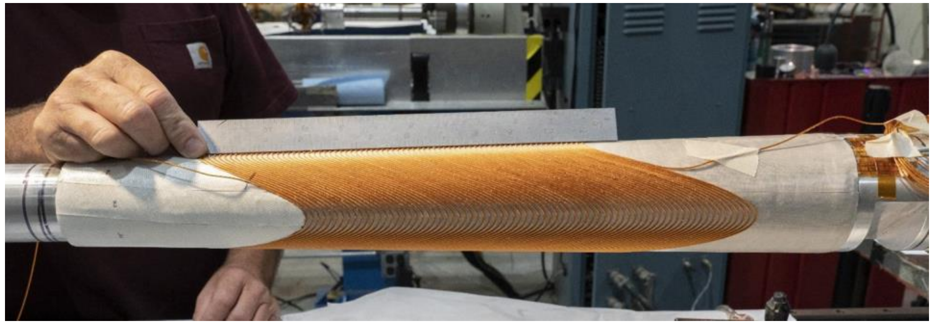


Field Measurements

- Tapered coils used for some low-β quads closest to IP (Q1APR/Q1ER).
- Use Double Helical coils produced via the BNL Direct Wind process (see below).
- R&D Test Coil: 4 layers, aperture varies from 60 to 80mm over 0.4 m length, gradient 43 T/m, 30-40 mm inner radius
- Although the aperture varies, the gradient is maintained constant.



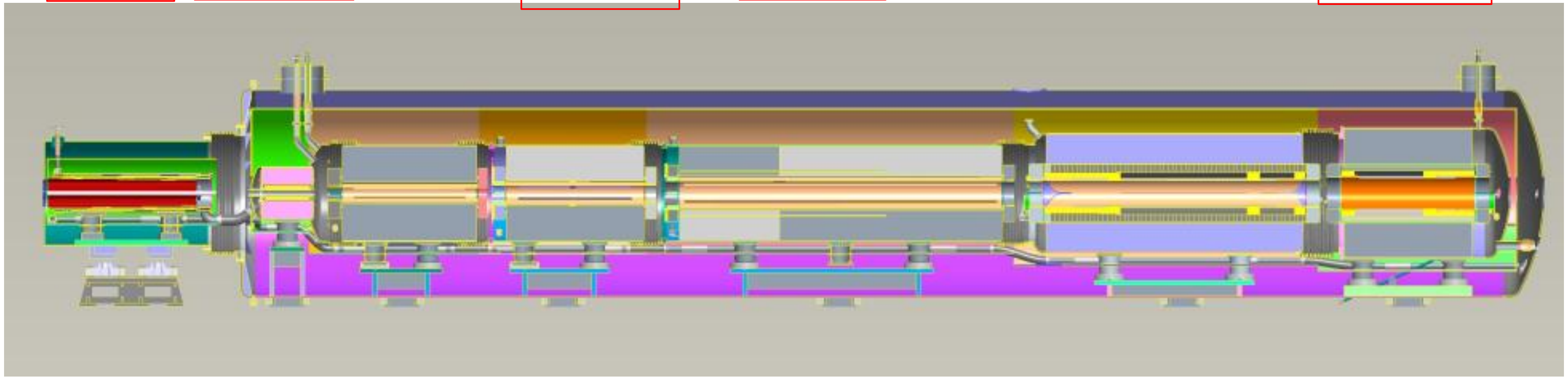
Calculated Coil Field



Tapered Quadrupole – no training, reached short sample at 960 A

Forward Side – side sectional view

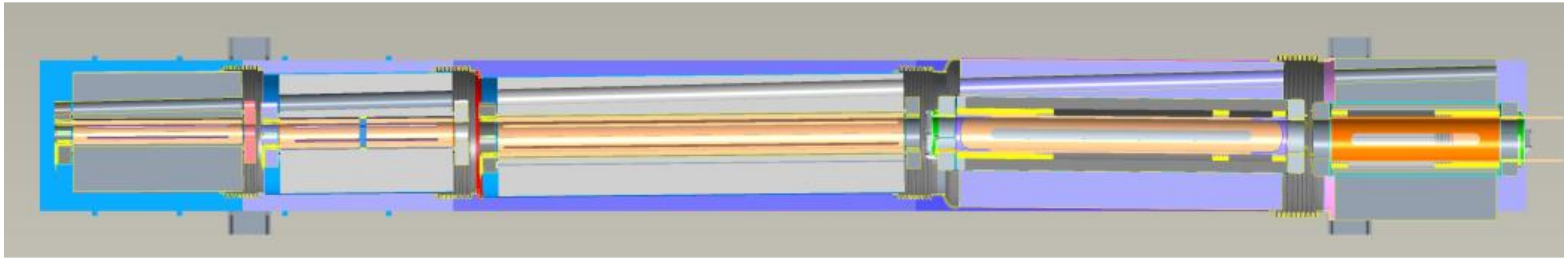
B0pF | B0ApF | Q1ApF | Q1BpF Q1eF | Q2pF | B1pF | B1ApF



Standalone Ø54” cryostat

- Common split Ø96” cryostat
- Cold mass adjustments within cryostat
- Each cold mass independently anchored
- Common helium vessel, with bellows between all magnets

Forward Side – top sectional view

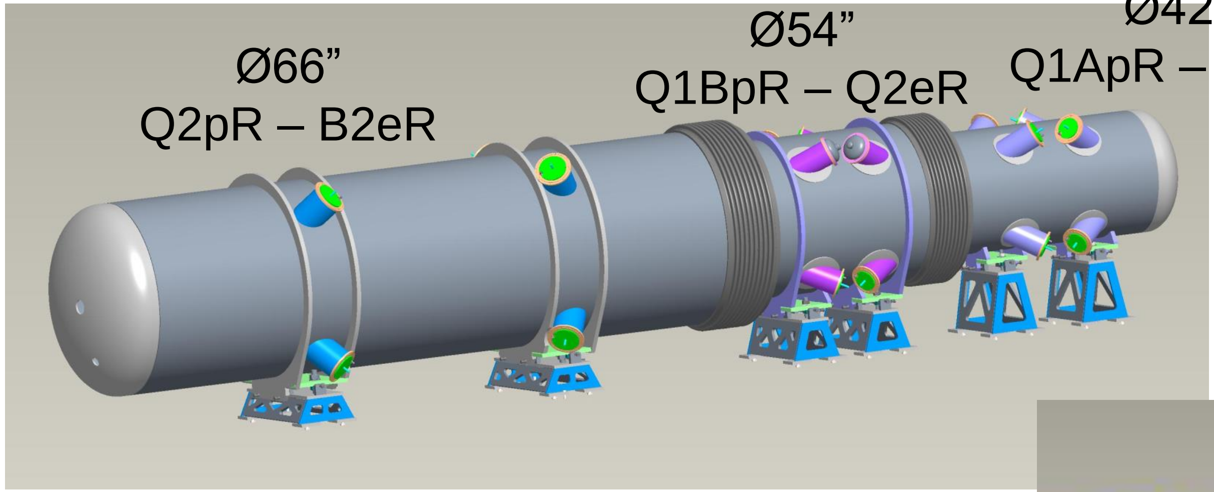


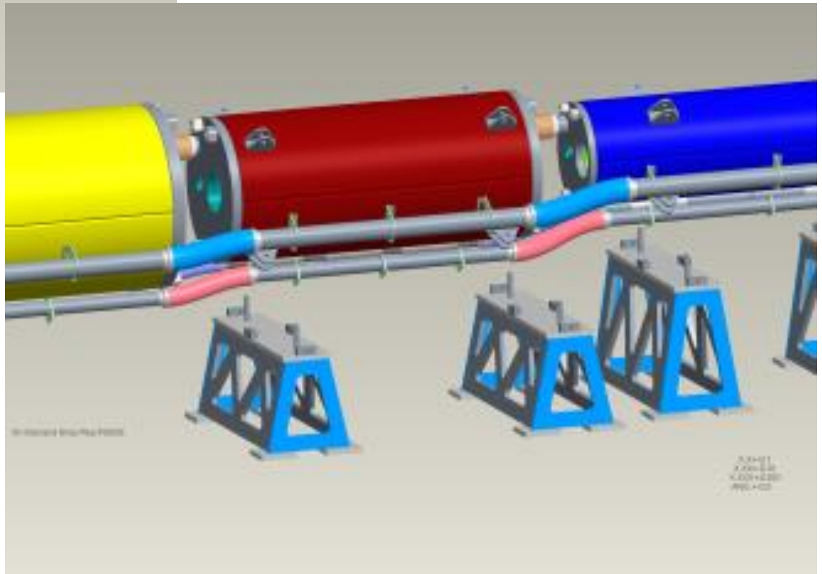
- Bellows between all magnets
- Space between end plates sufficient to weld inner helium vessels
- Electron beam straight despite hadron magnet offsets, angular differences

Rear Side Design / Installation

Separate cold masses - helium vessels

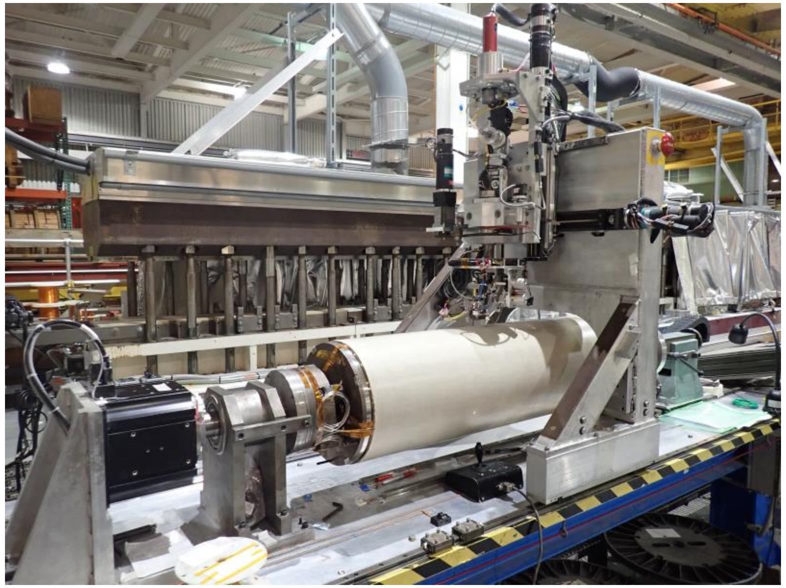
Separate circular cryostats with decreasing OD’s toward IP

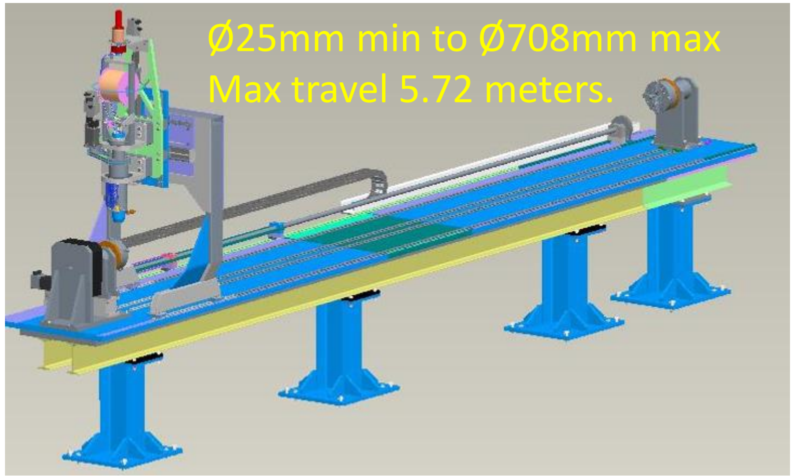




Direct Wind Coil Fabrication
(NbTi)

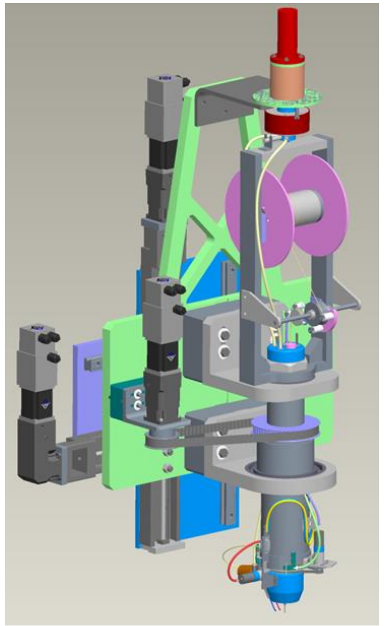
Long Winder



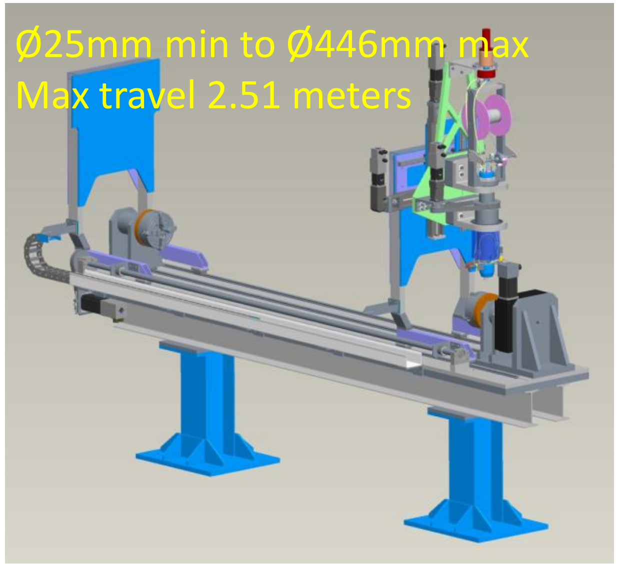


Presently upgrading computer hardware, software; increasing machine capacities & reliability

New winding heads commercial ultrasonic generator, increased capacity



Short Winder



Brookhaven National Laboratory

Rutherford Cable Coil Fabrication

(NbTi, Nb_3Sn)

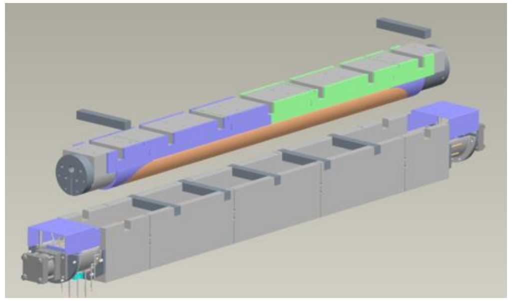
10m Shuttle Coil Winding Machine

4m Universal Coil Winding Machine

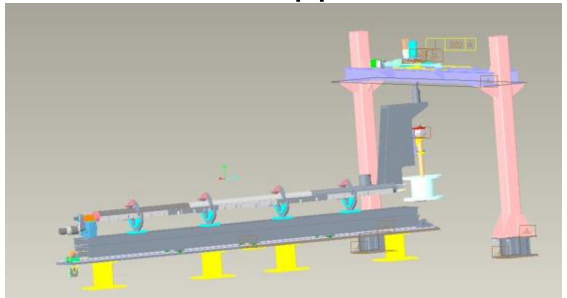
10m Coil Curing Press

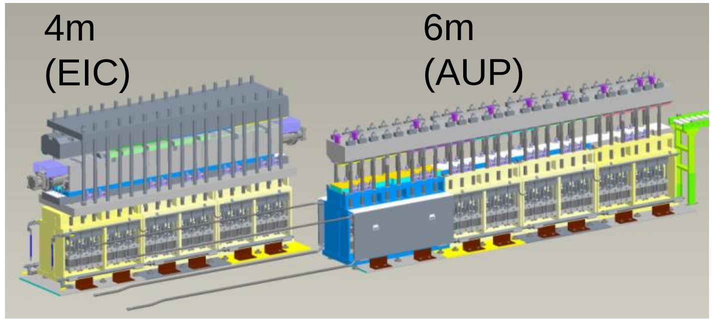
Curing sections easily separated
Coil size capacity increased for EIC (B1pF shown)

New mandrel & formblock
needed B1pF shown



New roller supports needed



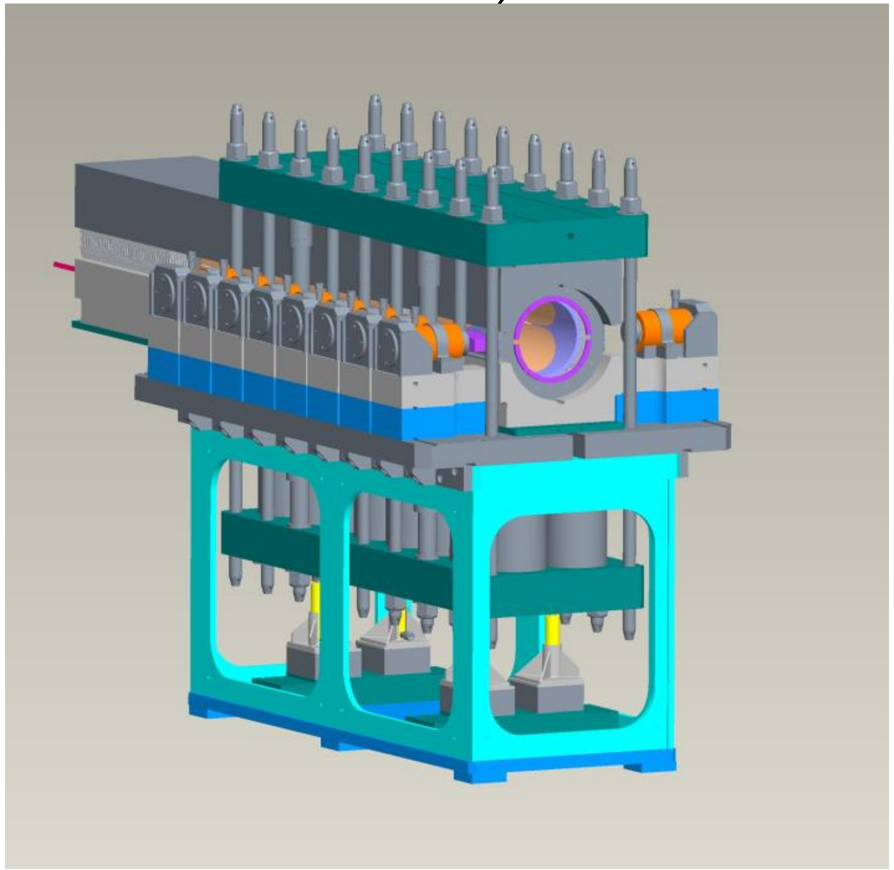


Brookhaven National Laboratory

Cable Magnet Collaring Press

Operational Collaring Press (side hydraulics removed, in storage)

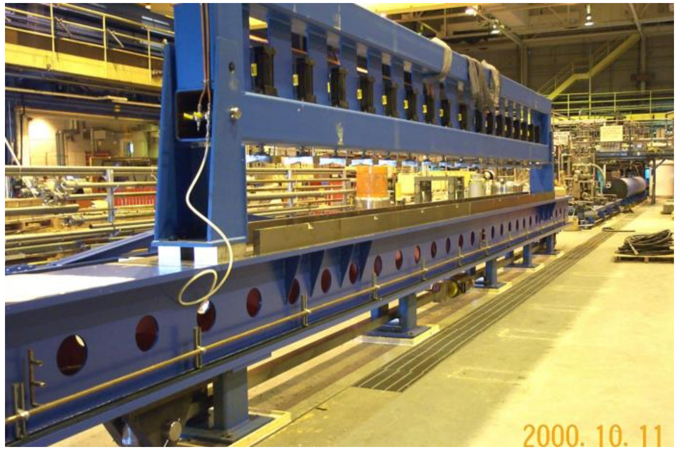
Size capacity increased for EIC (B1pF shown)



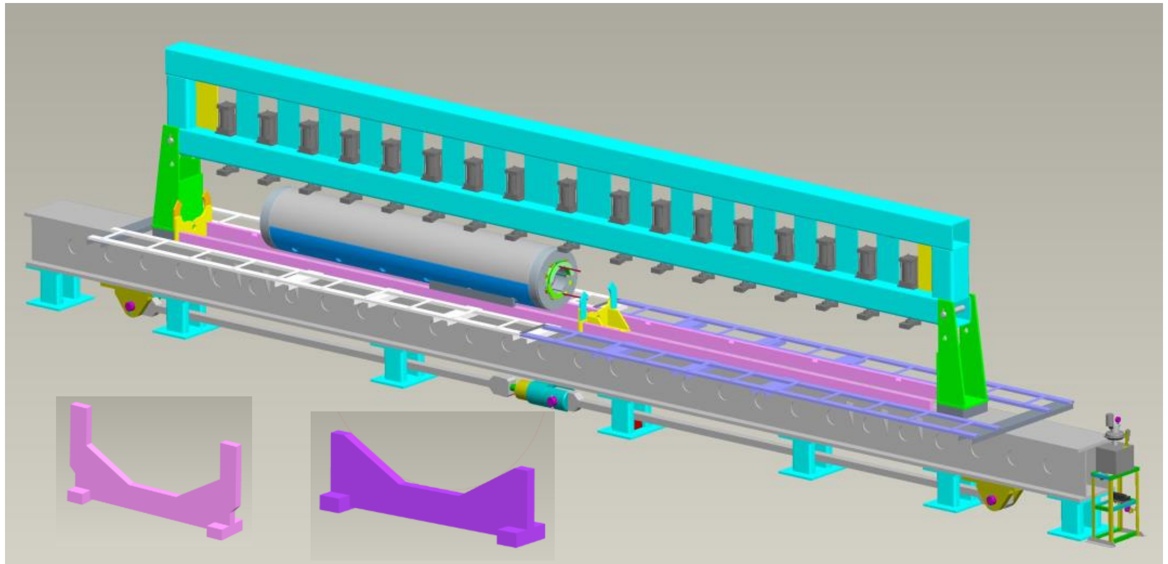
Brookhaven National Laboratory

Cold Mass Shell Welding Press

Operational 10m Welding Fixture



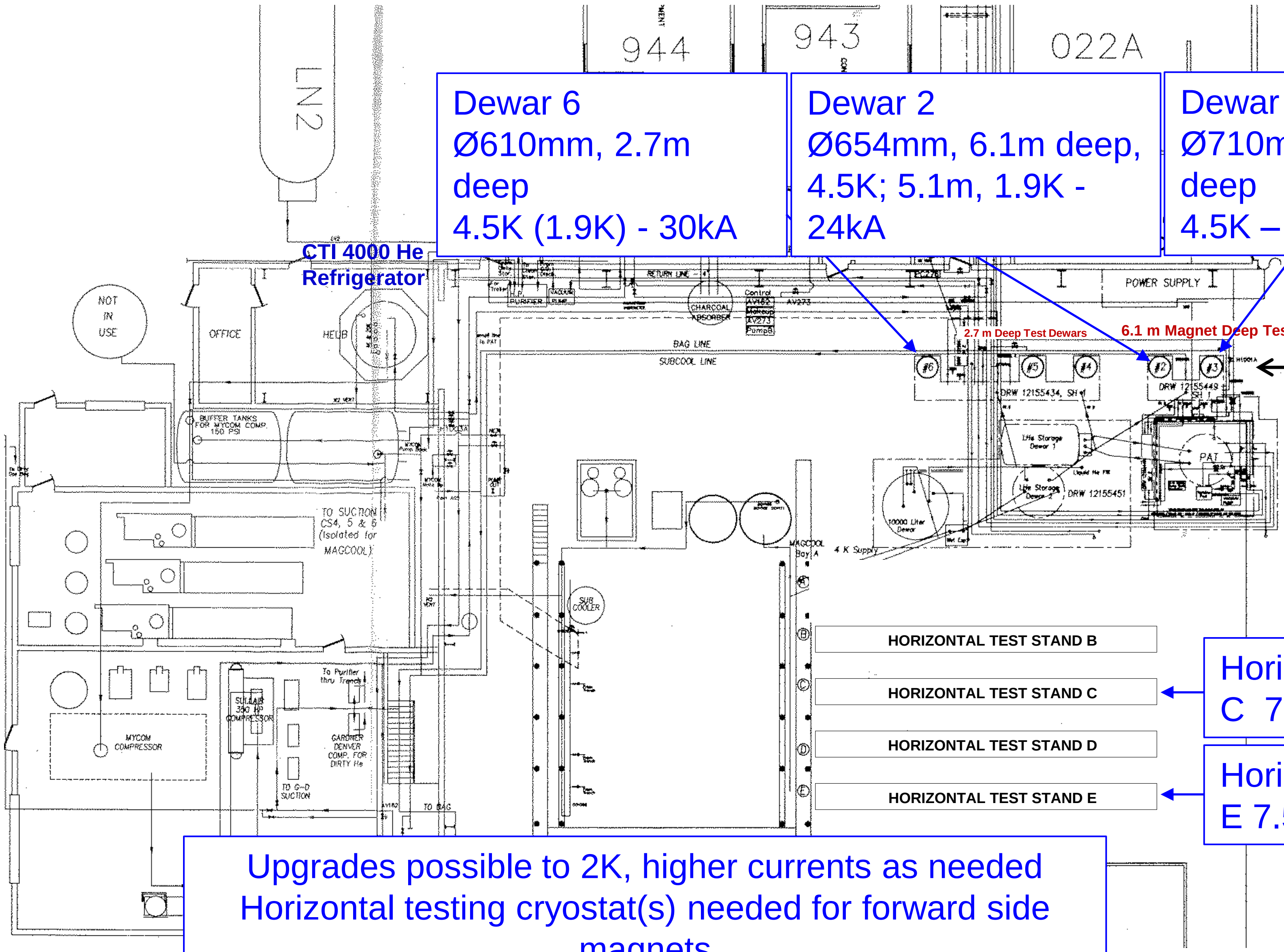
New contact tools, clamps needed for EIC



Brookhaven National Laboratory

Bldg 902 Facility, Magnet Testing Capacities

Nash "high capacity" helium vacuum Pump (1.9 K)



Dewar 6
Ø610mm, 2.7m deep
4.5K (1.9K) - 30kA

Dewar 2
Ø654mm, 6.1m deep, 4.5K; 5.1m, 1.9K - 24kA

Dewar 3
Ø710mm, 6.1m deep
4.5K – 8.5kA

CTI 4000 He Refrigerator

Vertical Test Dewars 2-6

Horiz. Test Stand C 7.5kA, 4.5K

Horiz. Test Stand E 7.5kA, 4.5K

Upgrades possible to 2K, higher currents as needed
Horizontal testing cryostat(s) needed for forward side magnets

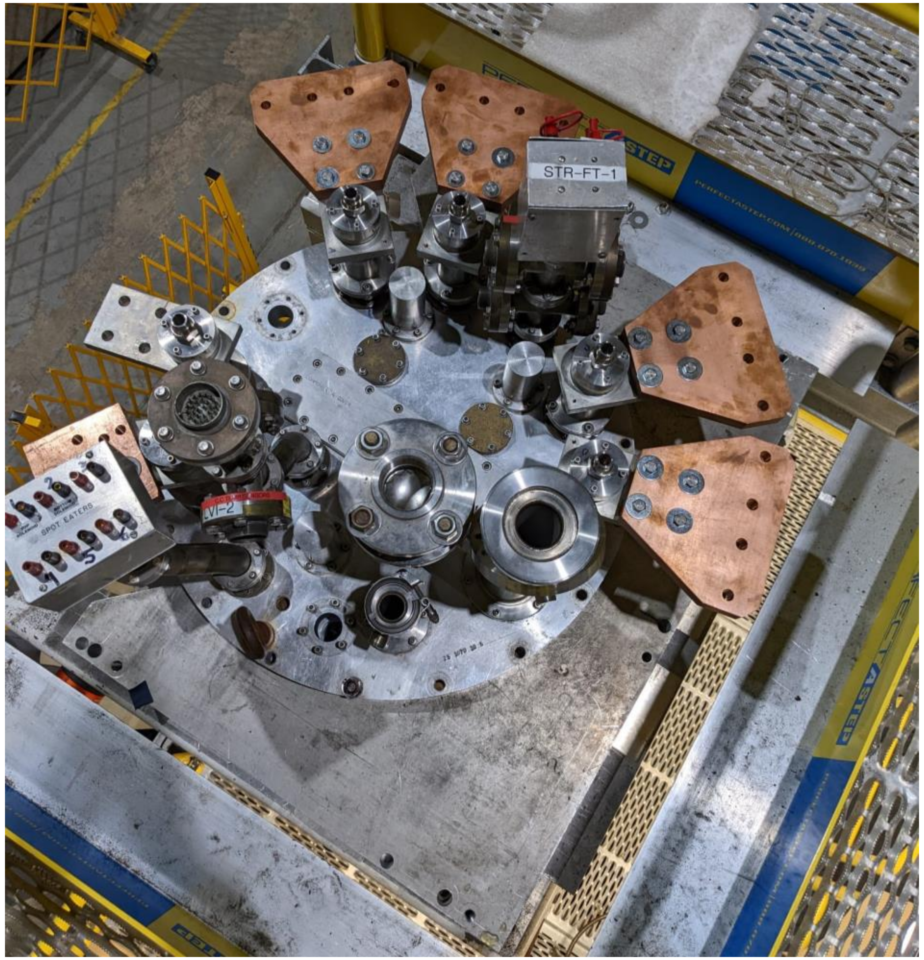
Brookhaven National Laboratory

DCC017 Common Coil Magnet

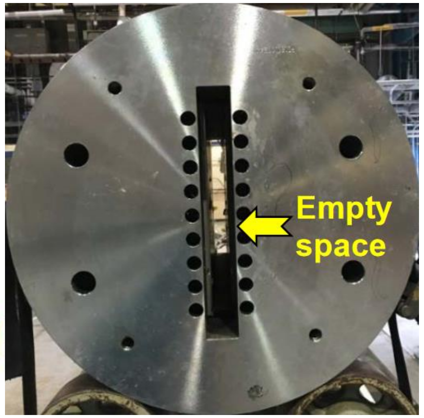
- Test Aperture: 30 mm X 335 mm
- Dipole field ≤ 10T.
- Max sample DC current 20kA.

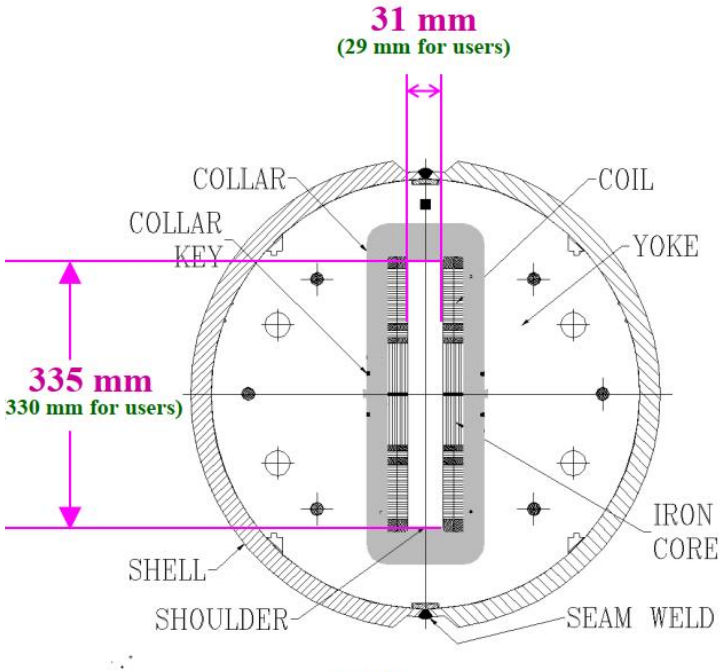
Side View

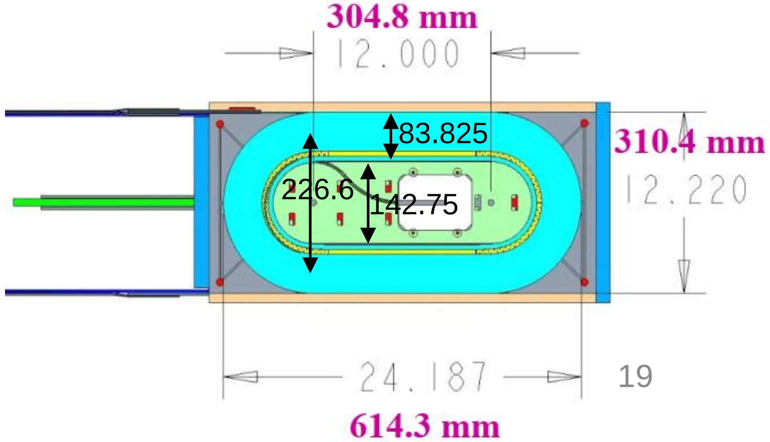
Top View



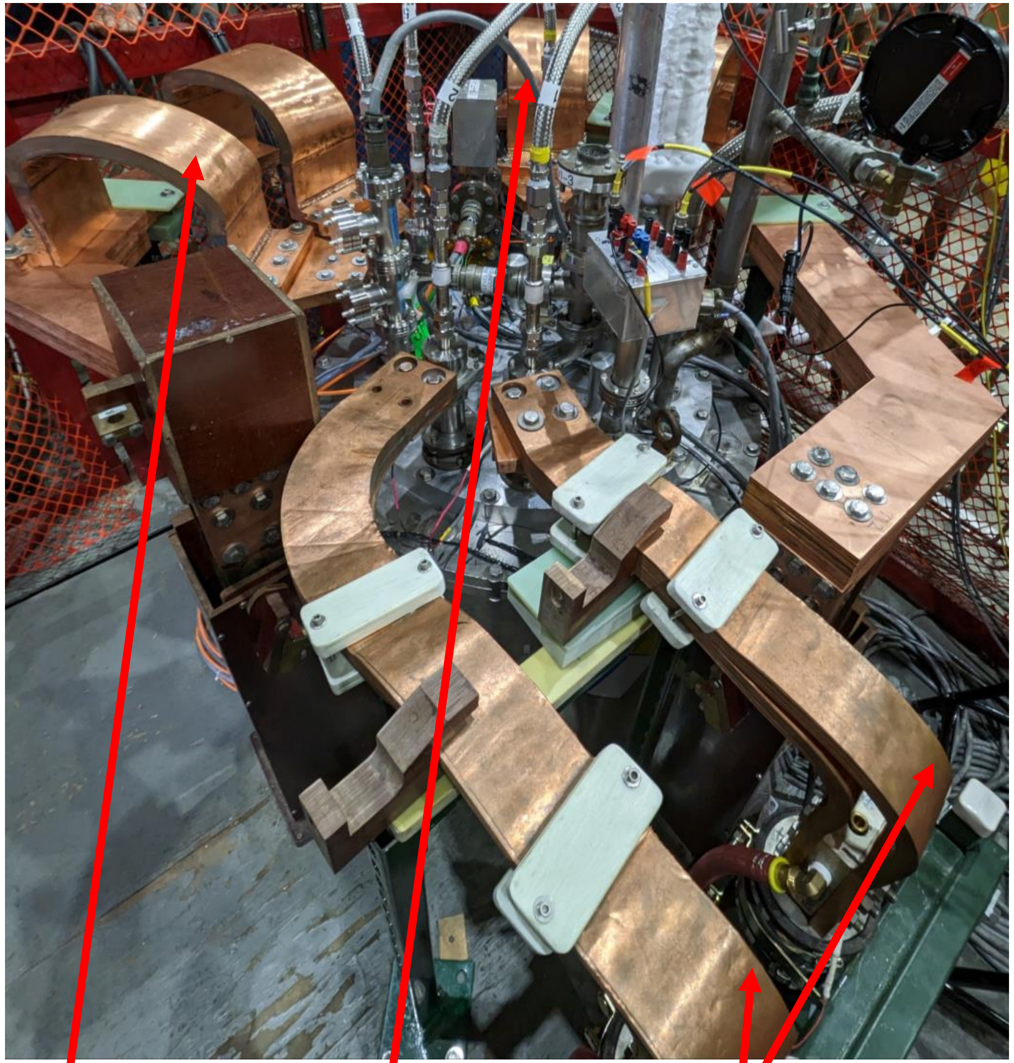
Bottom View





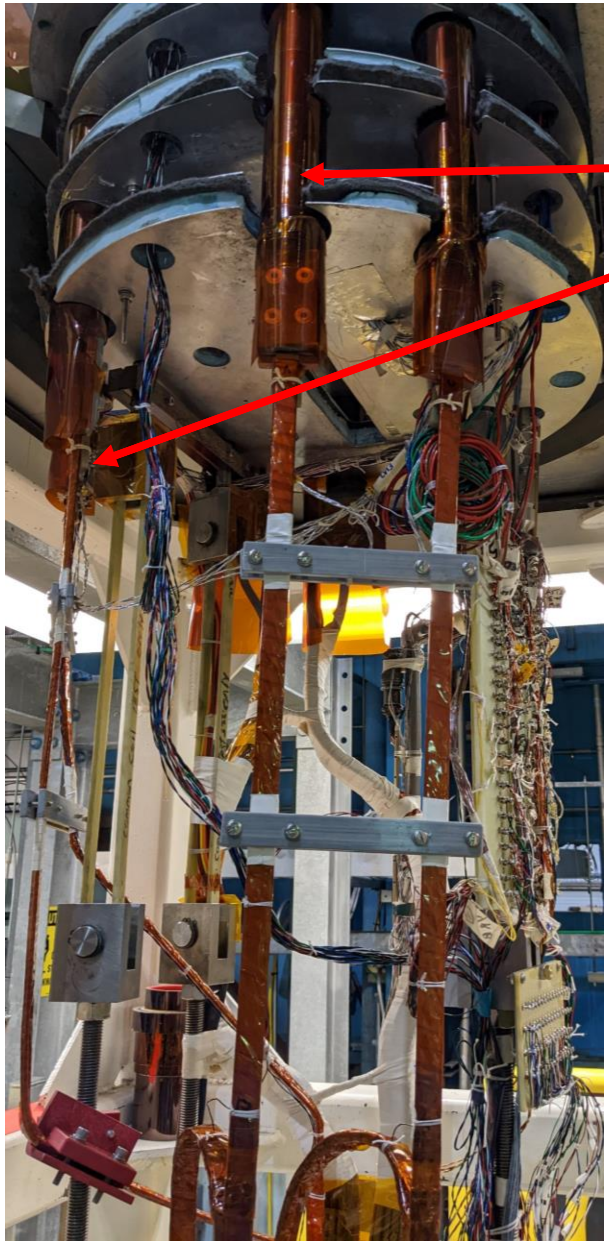


20kA and 10kA Power Leads



Sample leads 20kA

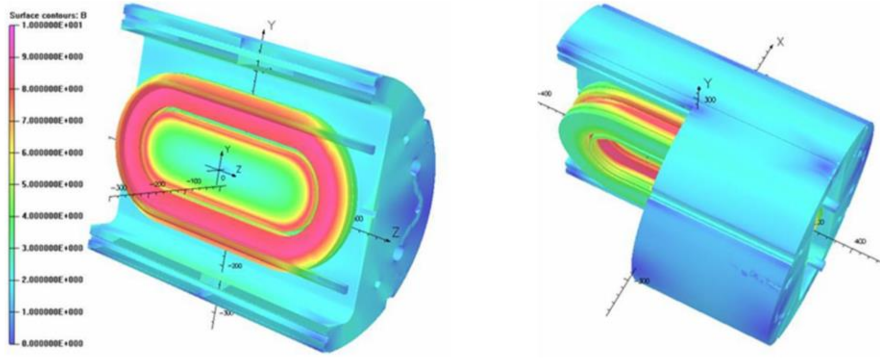
Common coil leads 10kA

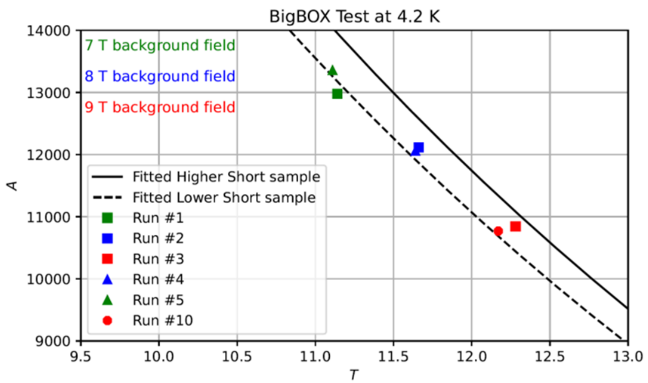


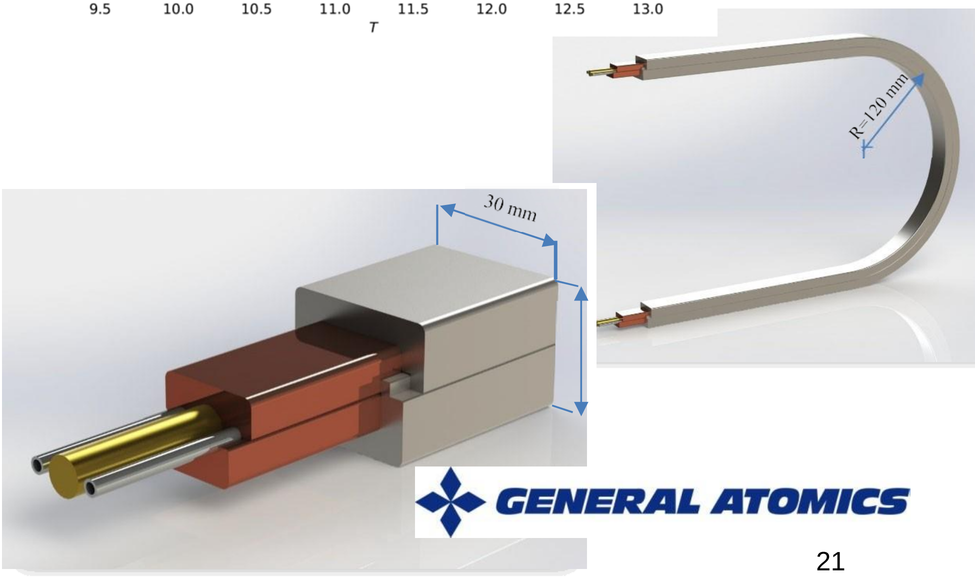
Six Gas cooled leads-10kA each

Cable Tests

- ✓ Twisted Stacked/Viper from CFS (INFUSE + ARPA-e) - two tests completed
- ✓ CORC from ACT (MDP) – Quench and technology studies - MDP test underway demonstrating new current performance of 15kA for CORC cable at zero field
- ✓ BigBOX Nb_3Sn wax sample test
- ➢ Cable-in-conduit for fusion magnets from BTG (SBIR)
- ➢ CICC from GA (INFUSE) – upcoming test







GENERAL ATOMICS

Brookhaven National Laboratory

Accelerator Magnets

BNL is engaged in current and emerging magnet programs that are further developed in Snowmass white papers

Magnet Development Program (MDP)- [2203.13985] A Strategic Approach to Advance Magnet Technology for Next Generation Colliders (arxiv.org)

- HTS/LTS hybrid magnets for >20T accelerators - [2203.08736] REBCO -- a silver bullet for our next high-field magnet and collider budget? (arxiv.org) [2203.08750] Common Coil Dipole for High Field Magnet Design and R&D (arxiv.org)
  - Comparative study
  - 10T high field dipole testing
- Cryogenic quench detection and data acquisition [2203.08309] Fiber-optic diagnostic system for future accelerator magnets (arxiv.org), [2203.08869] Advancing Superconducting Magnet Diagnostics for Future Colliders (arxiv.org)

Leading-Edge technology And Feasibility-directed Program (LEAF) – directed R&D - [2203.07654] White Paper on Leading-Edge technology And Feasibility-directed (LEAF) Program aimed at readiness demonstration for Energy Frontier Circular Colliders by the next decade (arxiv.org)

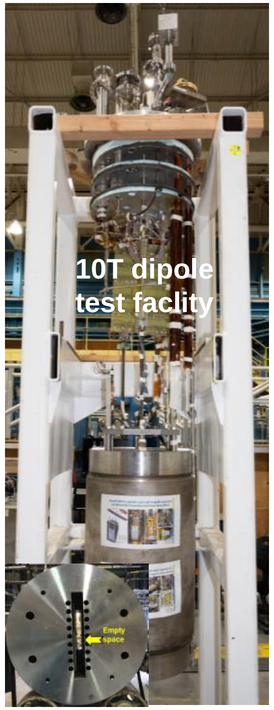
- Testing capabilities a key resource needed for magnet development
- Manufacturing/Industrialization experience from RHIC, EIC, AUP critical knowledge for tunnel-ready magnet technology

Highly integrated, precise IR magnet technology – leveraging EIC [2205.12847] Snowmass 2021 White Paper on Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation (arxiv.org)

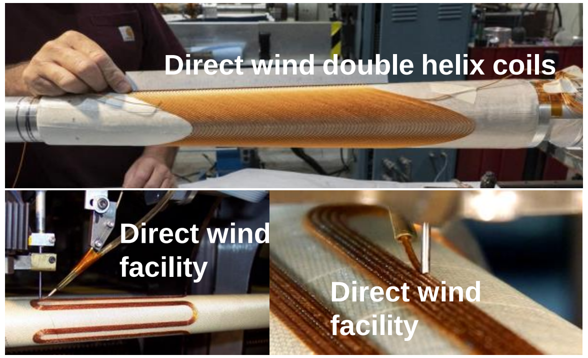
- Key for future potential accelerators with highly integrated IR – FCC-ee, Super KEK B (polarization physics upgrade)
- Investigating how to use other conductors beyond NbTi – A15 collaboration with KEK, STAR cable

Brookhaven National Laboratory

Vertical test facilities

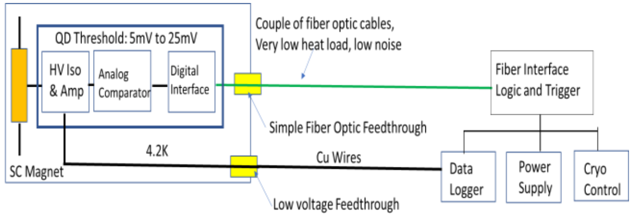


Direct wind for advanced IRs

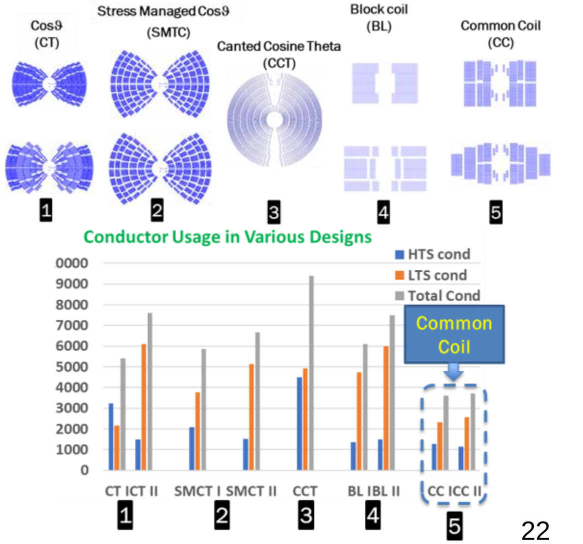


Magnet manufacturing and industrialization

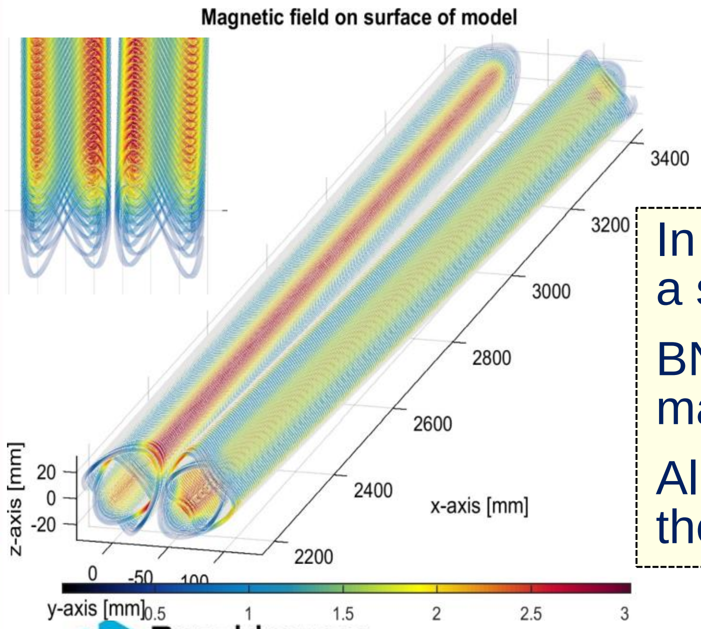
Low noise quench detection at Cryogenic temperatures



HTS/LTS hybrid comparative study at 20T



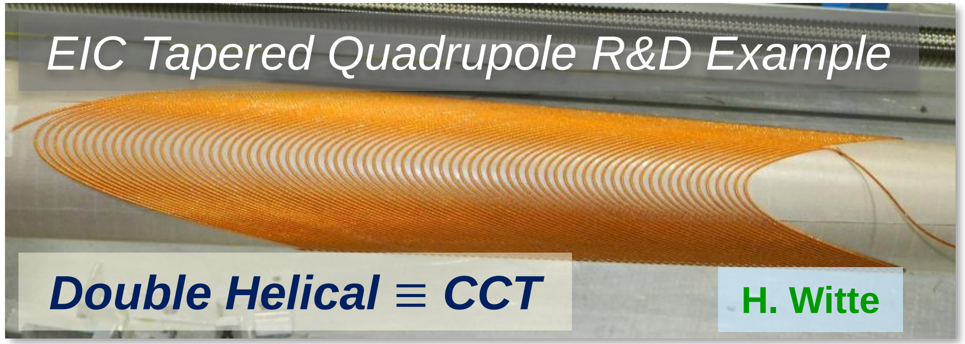
See Brett Parker's talk SC IR magnet systems



In addition to main quad coils, we need a slew of correctors (b_1, a_1, a_2...).

BNL Direct Wind process is natural for making the necessary correctors.

All coil designs must take into account the mutual external field cross talk.



Direct Wind Tapered Double Helical Coil

Future directions

BNL has a world class superconducting test facility that is available to the superconductivity community for magnet and conductor R&D

We have a strong history of partnering with industry and current leadership has significant industry experience

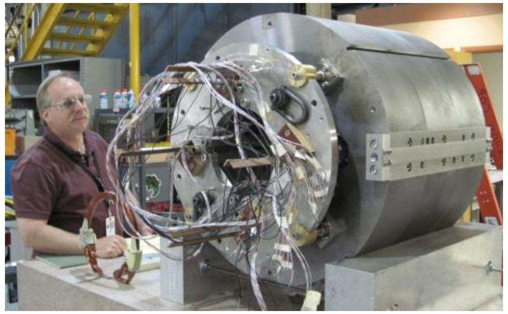
Long history and expertise in HTS magnet development

Full capabilities in everything from design to construction to testing

Unique direct wind technology for extremely compact advanced IR magnets

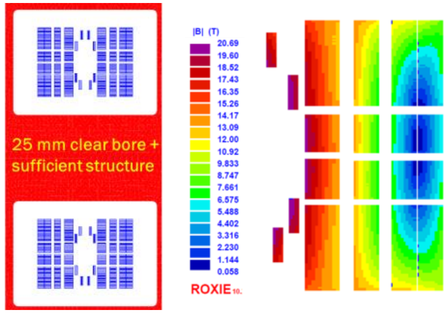
Continued development of multidisciplinary test facility for R&D in partnership with HEP, NP, FES, other national labs and industry

We have many magnet technologies and capabilities that can be used in a FCC



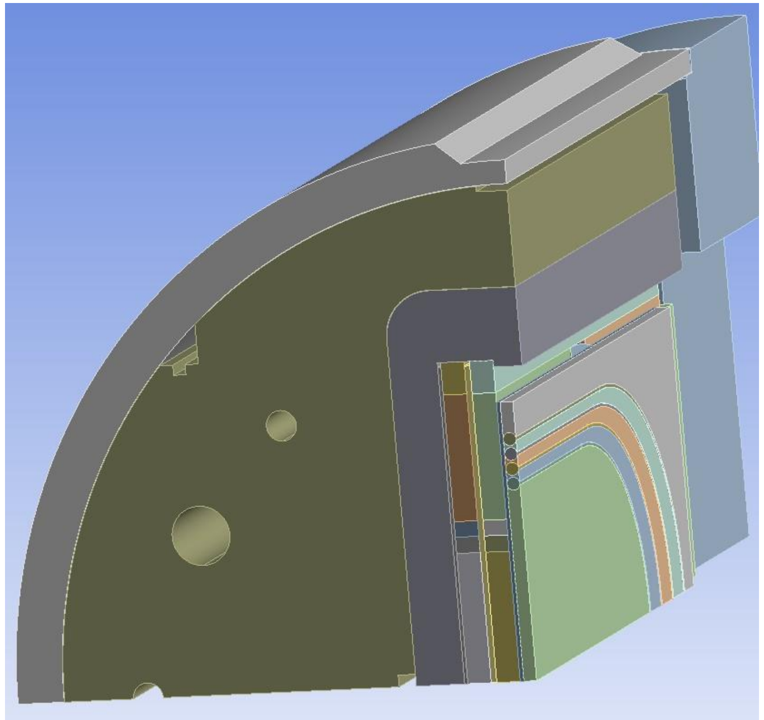
High temperature superconducting magnet for Facility for Rare Isotope Beams,

Relativistic Heavy Ion Collider – strong history of industrialization at Brookhaven



20T HTS/LTS hybrid dipole studies

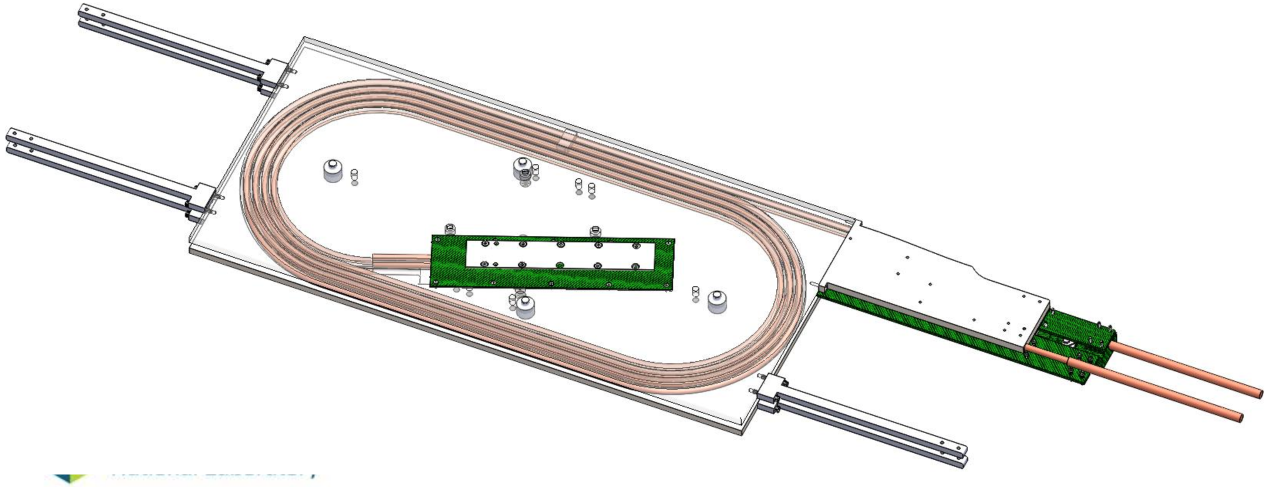
MDP CORC insert coil

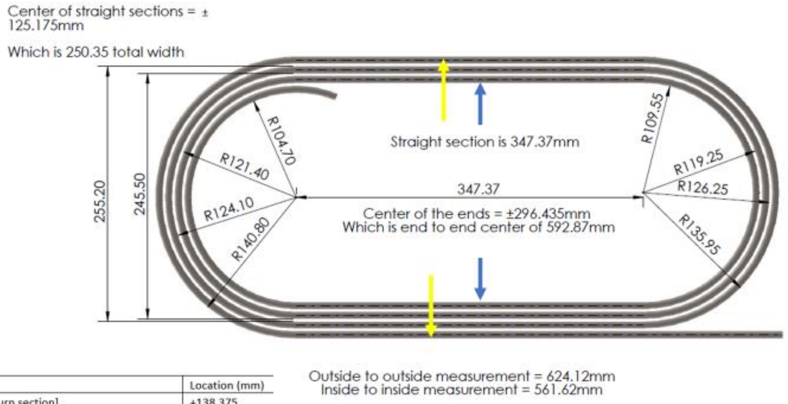


- The MDP insert coil consists of two pancake coils in racetrack geometry and is wound with a total of eight turns (four turns per pancake coil) of 24 tape CORC cables.
- The short sample critical current of the conductor is 11.04 kA at 10T field and 4.2 K temperature.
- The self-inductance of the magnet is 7.7 μH.

New records for CORC cable performance have been demonstrated:

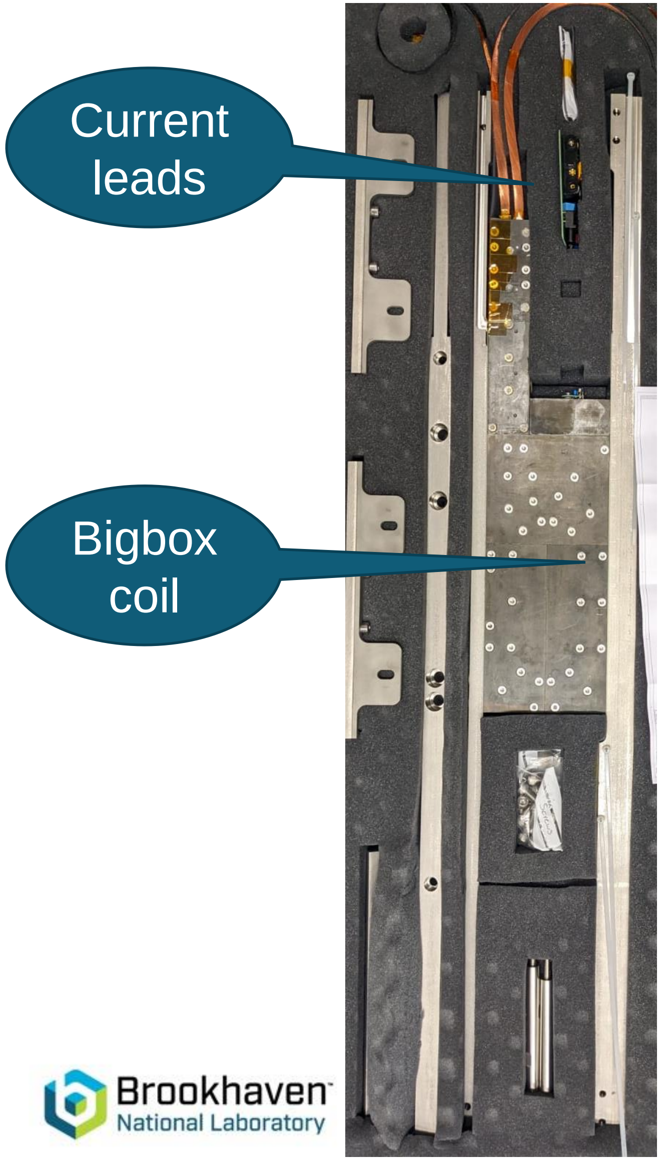
- 15kA/ 1.416 T at zero background field
- 12.87 kA CORC/6 kA Common Coil/ 7.06 T (5.66T from Common Coil and 1.4T from the self-field)
- 14.36kA/5 kA Common Coil/6.28T . (4.72T from Common Coil and 1.56T from the self-field)



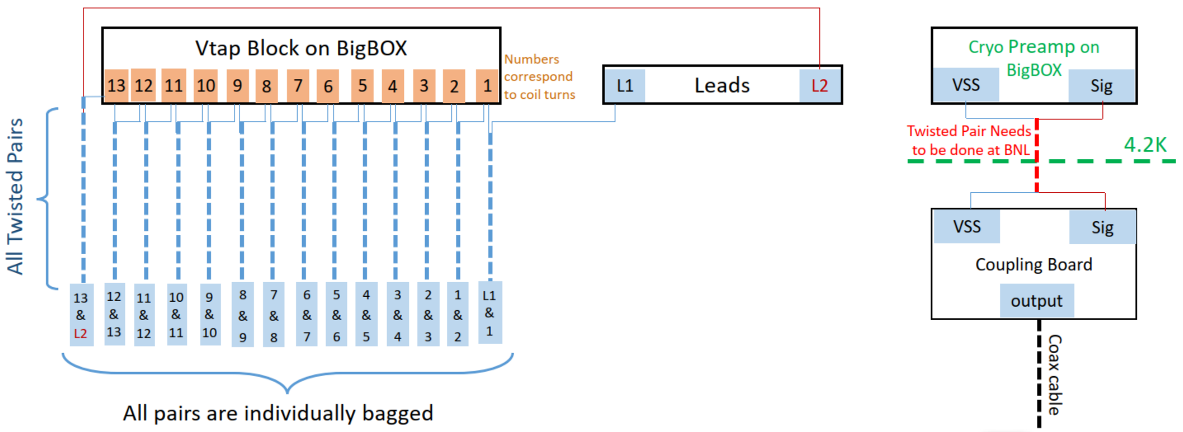


Position	Location (mm)
Top of Top [3 turn section]	+138.375
Bottom of Top [3 turn section]	+111.975
Top of Bottom [4 turn section]	-107.125
Bottom of Bottom [4 turn section]	-143.225

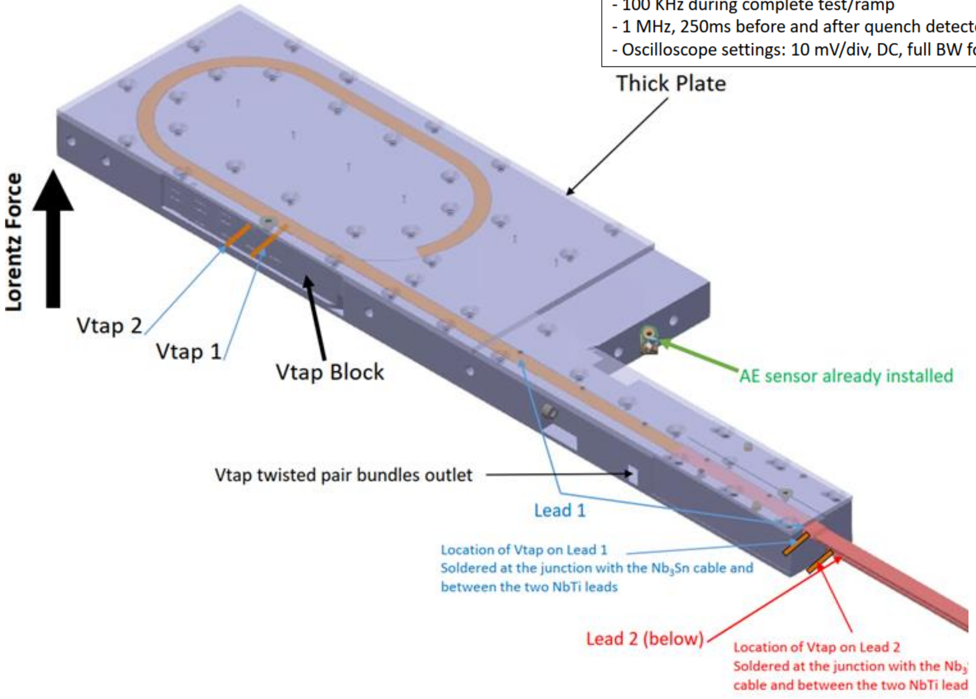
BIGBOX sample



Instrumentation Wiring of BigBOX



For testing the smaller BOX samples we record data using the following settings:
- Data acquisition of 16 bits
- 100 KHz during complete test/ramp
- 1 MHz, 250ms before and after quench detected
- Oscilloscope settings: 10 mV/div, DC, full BW for Vtaps and AE signals



- The coil is made of Nb_3Sn conductor but the leads coming out of the magnet are made of NbTi.
- **Voltage taps:** There are 14 pairs (28 wires) of voltage taps coming out of the coil.
- **Acoustic sensor**

Brookhaven National Laboratory

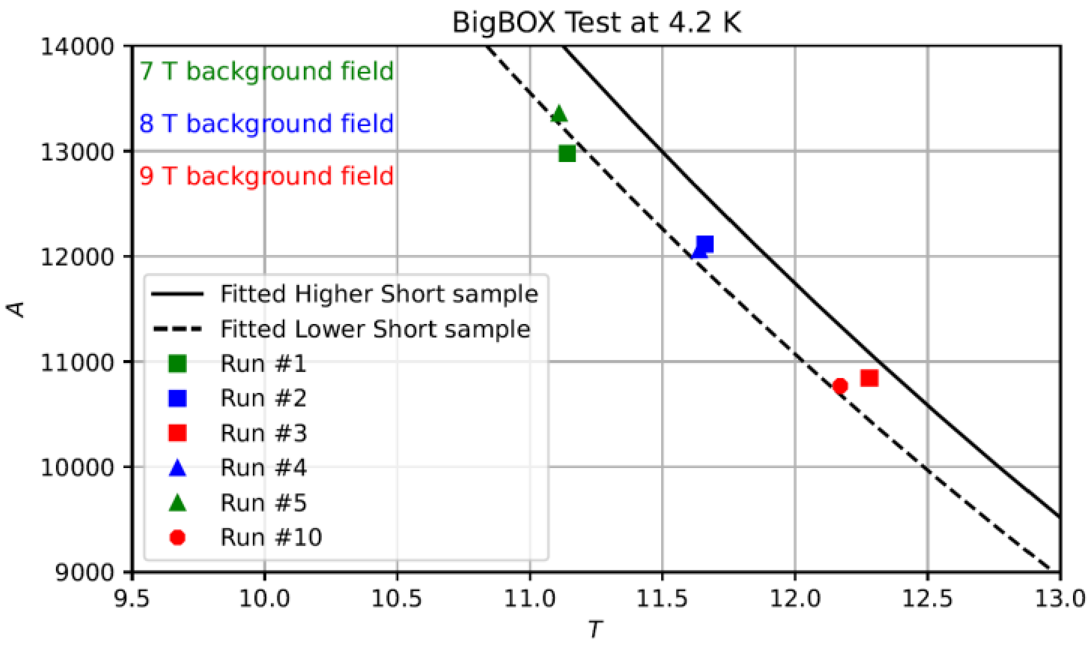
Main BigBOX Results

Experiment #	I_{CC} (kA)	I_{BB} (kA)	B_{CC} (T, estimated)	B_{BB}(T, estimated)	B_{total} (T, estimated)	Cycle #
1	7.195	12.979	6.79	3.89	10.69	1
2	8.04	12.118	7.59	3.64	11.23	2
3	9.124	10.845	8.62	3.25	11.87	3
4	8.0393	12.06	7.59	3.62	11.21	4
5	7.0398	13.359	6.65	4.01	10.66	5
4 EM cycles, ICC= 9 kA, IBB= 2kA to 10.3 kA to 2 kA and so on=> 11.59 T X 10.3 kA = 119.3 kN/m, three loading cycles						5+4
6	9.0395	10.769	8.54	3.23	11.77	10

<u>Abbreviations</u>

I_{CC}= current in common coil
B_{CC}= magnetic field in common coil
I_{BB}= Quench current in bigbox coil
B_{BB}= magnetic field in bigbox coil
B_{total}= combined field on superconductor

There was a trip during the fourth electromagnetic cycle



Brookhaven National Laboratory

Superconducting Solenoid for RHIC

- 200 mm coil id, 6.6 T ~2.4 m long NbTi solenoids designed, built and tested at magnet division (complex and demanding requirements; industry didn't build)
- No prototype. Two fully cryostated solenoid, successfully built and installed and are being used for electron cooling in RHIC

Parameters	Value
Wire, bare	1.78 mm X 1.14 mm
Wire, insulated	1.91 mm X 1.27 mm
Wire I_c specification (4.2 K, 7 T)	>700 A
Turn-to-turn spacing (axial)	1.98 mm
Turn-to-turn spacing (radial)	1.42 mm
Number of layers (main coil)	22 (11 double layers)
Additional trim layers in ends	4 (2 double layer)
Length of additional trim layers	173 mm on each end
Coil inner diameter	200 mm
Coil outer diameter	274 mm
Coil length	2360 mm
Yoke length	2450 mm
Maximum design field	6 T
Current for 6 T	~440 A
Peak Field on the conductor @ 6 T	~6.5 T
Computed Short Sample @4.2 K	~7.0 T
Stored energy @ 6 T	~1.4 MJ
Inductance	~14 Henry
Yoke inner diameter	330 mm
Yoke outer diameter	454 mm
Operating field (on the axis)	1 T to 6 T
Relative field errors on axis	<6 X 10^{-3}